

Short Course on Experimental Dynamic Substructuring

Module #1: Introduction



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Distinguished Member of Technical Staff, Sandia National Labs.

Short Course Notes For:

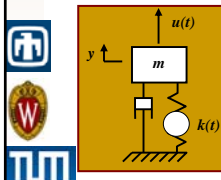
February 1, 2014, IMAC, Orlando, Florida

Outline / Schedule



NEG Micon, 2.0MW,
72m diameter, 1999

- 8:30 - **Mod01**: Introduction/Motivation - **Matt**
- 9:00 - **Mod02**: General Theory - **Daniel**
- 10:00 - **Mod03**: Industrial Examples - **Daniel**
 - 10:15 (15 min) Break
- 10:30 - **Mod04**: Matlab/Octave Exercises - **Matt**
- 11:00 - **Mod05**: Measurement Considerations - **Randy**
- 12:00 - **Mod06**: Hands on Exercise - **Matt**
 - 12:30-1:30 PM - Lunch Break
- 1:30 - **Mod07**: Decoupling Techniques - **Daniel**
- 2:30 - **Mod08**: Transmission Simulator - **Matt & Randy**
 - 3:15 (15 min) Break
- 3:30 - **Mod09a**: Estimating Fixed-Interface Modes - **Matt**
- 4:00 - **Mod09a**: Fixed Base - Another Application - **Randy**
- 4:30 - **Mod10**: Additional / Advanced Concepts
 - (20 min) Source description, Blocked forces, etc... **Daniel**
 - (20 min) Nonlinear Substructuring and NNMs - **Matt**
 - (20 min) Q & A and/or continue hand-on measurements/analysis



About the Instructors

- **Instructor**
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Informal Survey

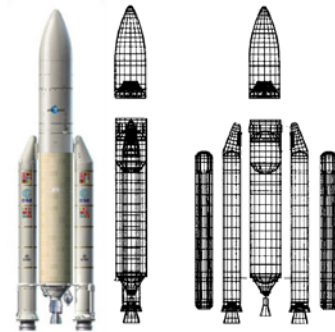
Have you:

- Had an undergraduate-level class on vibrations?
- Had a graduate-level class on vibrations?
- Had a graduate-level class on finite element analysis?
Experience with FEA?
- Ever performed a modal test? Regularly?
- Approach for this short course
 - 80% Lecture , 20% Guided exploration
 - Files needed for the examples can be obtained at:
 - <http://substructure.engr.wisc.edu/> in the "Tutorials" section:
 - <http://substructure.engr.wisc.edu/substwiki/index.php/Tutorials>
- Assessment :
 - You will be asked to complete a short questionnaire within a few days of the short course to help the instructors to evaluate its effectiveness.

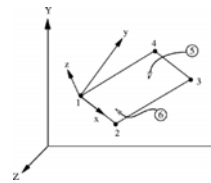


What is Substructuring?

- Substructuring is a process whereby individual components of a structure are analyzed or tested separately and then combined to predict the response of the built-up structure.
 - Reduced Order Modeling: create an approximation to a model to reduce the computational burden
- Analytical substructuring forms the basis of the Finite Element Method, and related techniques, such as the Craig-Bampton method, have been key components of structural analysis for over 40 years.
- **Experimental/Analytical Substructuring** is a far less common variant where a model for one or more subcomponents is derived experimentally.



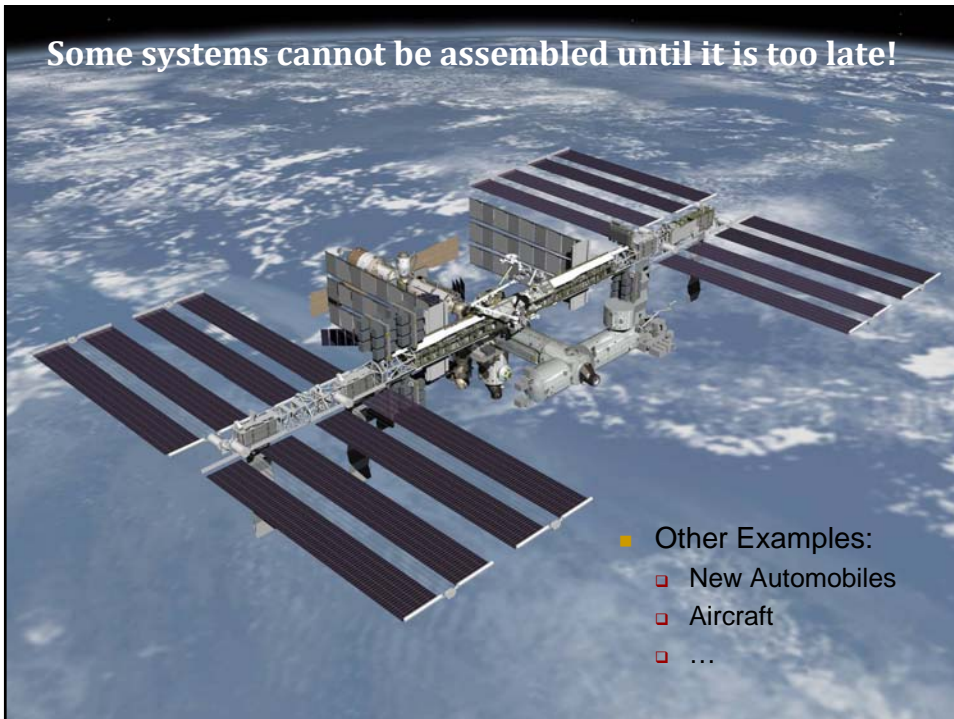
Ariane 5 Launch Vehicle (ESA)
and diagram depicting
potential substructures



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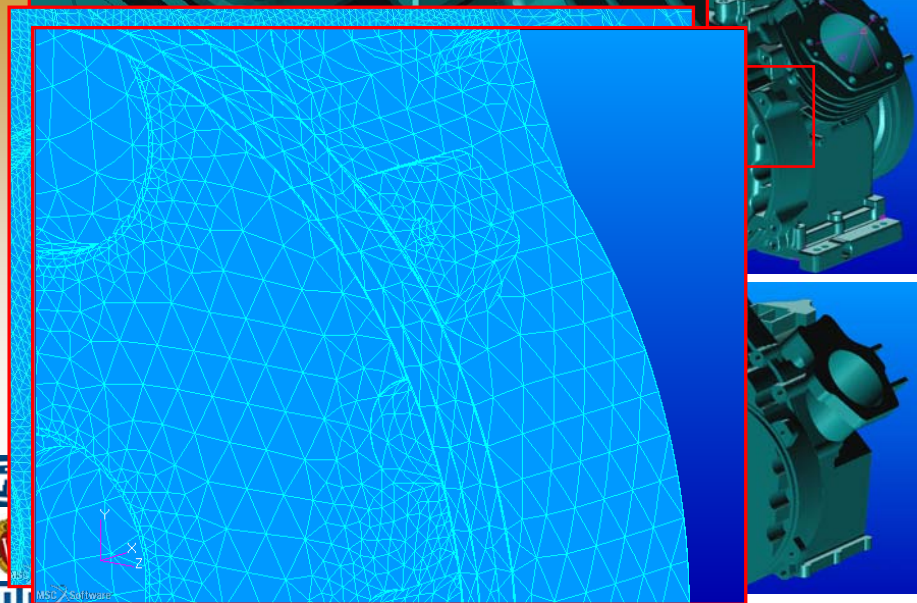
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Some systems cannot be assembled until it is too late!



- Other Examples:
 - New Automobiles
 - Aircraft
 - ...

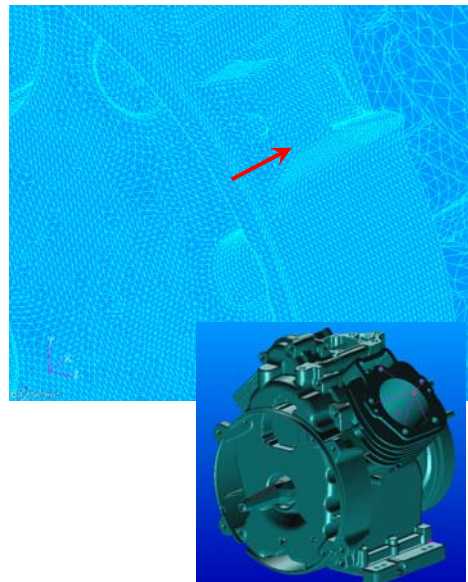
Reduced Order Models



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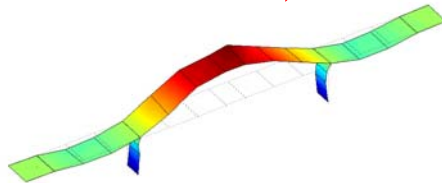
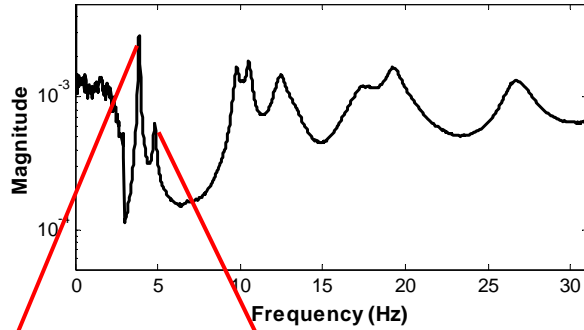
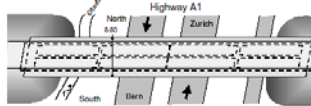
Basics of Substructuring / Reduced Order Modeling

- A complete FEA model allows for arbitrary motion of any node of the structure.
- A substructure or reduced order model can be more efficient by capturing only those motions that are likely in the application of interest.
- This is especially relevant to structural dynamics, where the deformations observed are often the net effect of only a few vibration modes.



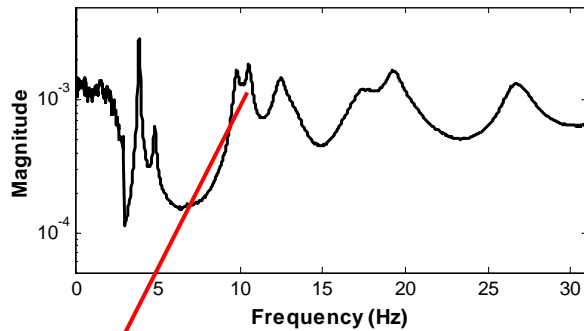
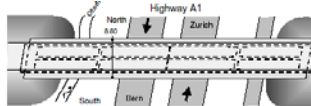
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Example – Swiss Highway Bridge

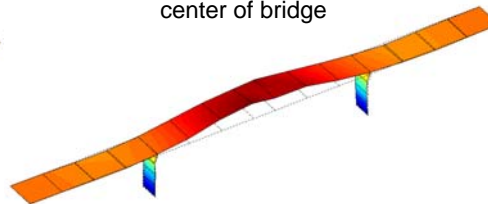
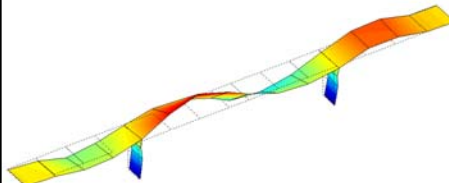


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Example – Swiss Highway Bridge



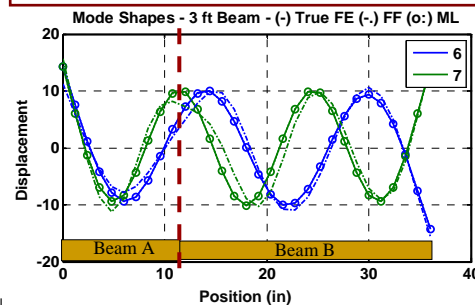
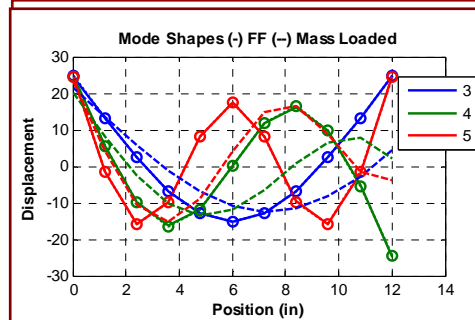
Response to impulse applied to center of bridge



Modes as Basis Vectors: A Simple Example

Mode #	Nat. Freq (Hz)		Error (%)
	FEA	FF	E (%) FF
3	121.0	128.0	5.8%
4	333.3	364.0	9.2%
5	653.3	658.8	0.8%
6	1079.7	1130.8	4.7%
7	1612.4	1781.8	10.5%
8	2251.3	2282.0	1.4%
9	2996.3	3176.3	6.0%
10	3847.2	4396.0	14.3%
11	4803.7	4934.3	2.7%

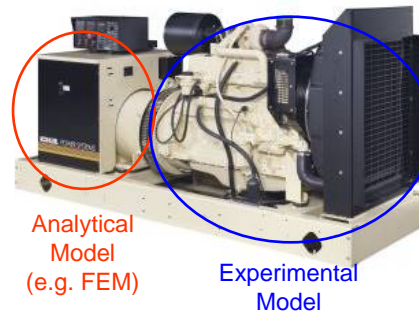
- A reduction basis must be carefully selected to produce accurate results!



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Experimental – Analytical Substructuring

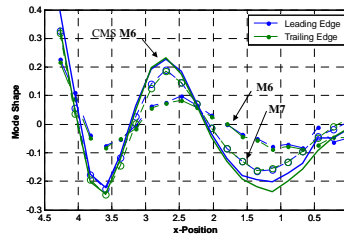
- Often we are tasked with analyzing systems where one or more components are very difficult to model analytically.
 - Intricate geometry
 - Drawings proprietary or unavailable
 - Unknown material properties
 - Bolted joints with complicated stick-slip behavior
 - ...
- These components can potentially be replaced with an experimentally derived model.



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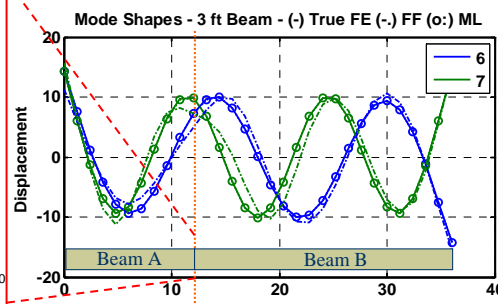
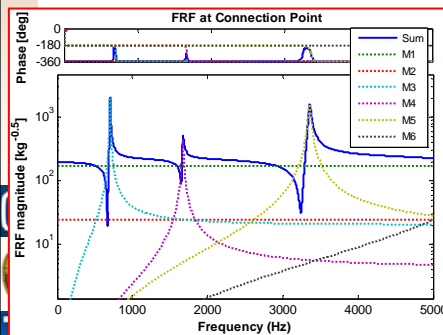
Experimental Substructuring CHALLENGES

- Approach is limited to motions that can be measured accurately.
 - Free-free boundary conditions:
 - Easy to reproduce experimentally
 - Poor accuracy (slow convergence)
 - Can be augmented with attachment modes (residual flexibility)
 - Fixed interface modes
 - More efficient for rigidly connected substructures
 - Difficult or impossible to realize experimentally
 - Must be supplemented with constraint modes which are even more challenging to measure!
- Measurements are subject to noise / errors.
 - How do we design tests to reduce errors?
 - Can an adequate model be created in the presence of inevitable measurement errors?
- Substructure models require the rotation at the connection point, which is challenging to measure reliably!



Inter-relationships between FBS and MS

- Modal substructuring is known to be accurate if the modes of the substructures form an adequate basis for the built-up system's motion.
- On the other hand, Frequency Based Substructuring is theoretically exact so long as the FRFs at the connection points have been captured accurately.
- Comparing these requirements:
 - It seems that the FRFs must be incredibly precise if modes well above the measured frequency band are influential.
 - Residuals can be included in MS or FBS to help account for these effects.



Mathematics Notation used in this Short Course

- This course uses the following mathematical notation (as much as possible) although some deviations will be necessary:
 - Scalar variables italic: x, y, z, \dots
 - Vectors and Matrices upright: x, y, A, B, \dots
 - Exponentially Modulated Periodic (EMP) vectors and matrices (used to derive harmonic transfer function, etc...) capital bold upright: $\mathbf{X}, \mathbf{A}, \dots$
 - When possible lower case for time-varying vectors and upper case for vectors that are functions of frequency: $x(t), X(\omega)$
- **Our goal is for you to learn and gain new skills.
Please feel free to ask questions at any time!**

